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DARPA PROGRAM INTELLIGENT TASK AUTOMATION (ITA)*

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ABSTRACT

The establishment of a science and technology base for many aspects of defense manufacturing and for adapting intelligent systems for complex military operational tasks is a cornerstone effort of advanced research with great national significance. This presentation provides an overview of the efforts of the Defense Advanced Research Projects Agency (DARPA) and the Air Force Wright Aeronautical Laboratories (AFWAL) to plan and fund technology development for a substantial leap in Intelligent Task Automation (ITA). In addressing the needs for high productivity in manufacturing and robust applications to complex military tasks, the ITA program develops and integrates the generic technologies impacting, gripping, sensing, viewing, recognizing and understanding the environment, controlling manipulation, and intelligently providing command of the task.

INTRODUCTION

Automation and automatic control of industrial processes has been permeated by robotic concepts, with the intent of providing greater industrial productivity for a "reindustrialization in America." Flamboyant feature articles in the popular press and some technical literature raise the expectation that future robots will be sophisticated, dexterous, adaptable and intelligence for a wide gamut of industrial, military and community operations -- on Earth and in space. Some caution is needed in estimating the time scale for those events. It is necessary to take into account the inertial forces that resist change in production methods, military

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operations and social behavior. These conservative forces limit the considerable support that is necessary to transfer what is possible in the laboratory into actual practice. DARPA's role is to remove some of the constraints so that these promises of the future are realized sooner and more fully.

Forecasts of unfolding robot technology were brought under rational considerations in a recent "Overview" of robotics prepared by the National Bureau of Standards in conjunction with the National Aeronautics and Space Administration (Gervater, 1982). In this report, the industrial needs and expectations are compared with directions being taken in research and development. Emerging in the foreseen evolution are hands with improved dexterity, the advanced control systems to support them, the vision and touch sensors to support the programmed control, and (later) a self-planning for intelligently supporting more general commands.

There are various tasks being considered for application of the expected intelligent capabilities in automation. In manufacturing they range from providing speed and economy in mass production assembly tasks to totally automating inventory and tool management in manufacturing. In military operations they include handling such complex tasks as reconnaissance and sweeping mine fields.

Getting the technology trends to provide the anticipated payoffs in automation of intelligent tasks is not straightforward. In terms of R&D economics, there are strenuous issues as to whether the advanced concepts and developments providing economical soundness of approach for manufacturing industries will sufficiently support a robust realization of the possibilities. For instance, re-engineering the production methods within existing plants presents considerable economic competition for the robotic alternatives of installing flexible automation that copes with the unstructured environment. Manufacturing, for some time to come, may in the large remain permissive enough to support vision with structured light or to take advantage of 2-D images at fixed range -- in spite of the significant efforts in laboratories to secure the necessary technologies for understanding 3-D images with grey scale.

DARPA'S ROLE

As the central research organization for the Department of Defense, DARPA has a primary responsibility to support advanced research bearing on manufacturing because of the significant military value of the industrial base to military force structure. The present joint project linking DARPA with the Air Force Wright Aeronautical Laboratories (AFWAL) at Wright-Patterson Air Force Base is in large part due to the challenge of meeting our nation's defense readiness goals through integrated computer-aided manufacturing (ICAM). Solving problems in the production base and developing tomorrow's new, more efficient manufacturing processes for the military hardware that will be required at the turn of the century is a vital support activity for DARPA.

In addition, the military services look to DARPA for the kinds of technological advances that will extend and enhance operational capabilities in the combat environment. Presently, the military is looking into the implications of robotic technology and recognizes that today's technology, except for a few innovations in space, is dedicated to the assembly line and will remain there unless military needs are defined and developments funded.

For the near term, the military is expected to adopt the industrial robotic technologies for the same advantages found in manufacturing -- relieving personnel from hazardous tasks that demand time-critical effort. Handling ammunition resupply for self-propelled artillery or tanks has been considered as a direct application of the industrial robots. The continuous-path capabilities currently available appear suited to transferring ammunition from armored resupply vehicles to armored combat vehicles in the battlefield environment under possible threat of nuclear, biological, or chemical (NBC) actions. Essentially, these tasks call for the mobile mounting of an industrial robot for forward operations with the combat support forces.

But the military is especially interested in such broader applications of automation technologies as providing intelligent solutions to the Army's countermine problem. Concepts for solving this problem will go beyond the physical handling of material and tools to include the Army's thinking about automating the "land rover." Where initially, remotely controlled mine clearing may be obtained by outfitting armored vehicles with a roller or mine plow and dispensing mine-clearing line charges, the eventual concepts will be intelligent about the overall countermine objective of establishing passage through a mined area. Instead of blindly clearing an intended area, many mines could be located by detecting the mine "footprint" with appropriate sensors and then marking the mine for avoidance. This intelligent approach would be based on an integrated automation of the roving vehicle, information handling, and physical handling of markers and cover material at a mine location.

In pointing out the enormous possible breadth of applications, it is intended not to thoroughly define the scope for using DARPA's resources, but rather to provide some insight to the range of choice being addressed. The Defense Sciences Office (DSO) has arrived at a focus in terms of the following concept for Intelligent Task Automation (ITA). While not excluding other interests, this focus is usefully providing a point of departure for prioritizing technologies opportunities. The DSO program is coordinated with the efforts of the Information Processing Techniques Office (IPTO) of DARPA. IPTO's programs in artificial intelligence, information processing and computer technologies have an important impact on the ITA goals. The emphasis of DSO is presently on device subsystems with ITA capabilities and, in the future, on complete systems.

THE CONCEPT OF INTELLIGENT TASK AUTOMATION

Among the technological advances in automation promising operational payoffs in either defense manufacturing or military operations are some potential advances that may not get bridged "naturally" by industrial support and incentives. As pointed out above, such tradeoffs in the industrial environment as using advanced robotic sensing versus engineering the robot's environment are not likely to arrive at the same critical demand that the military has for sensor driven control. Without the means to structure its environment, the military robot is confronted with obstacles, clutter, or unknown conditions; and its target will have highly variable character. Exploitation of the kinds of sensory controls outlined by D. Nitzan (1981) will be a military necessity; and it can be anticipated that the economic tradeoffs for industry will also eventually prove out the advantages of gaining flexibility with extensive sensing.

Simply, DARPA is recognizing that some technological opportunities are apparently missing investments because of the competition of attention to nearterm engineering "problems." Technologies suitable for military operations and the longer term goals for flexible manufacturing should not take advantage of structures for the environment. For example, the "bowl" feeder used in partsorting in industrial assembly is unlikely to work out for an ammunition handler in the combat arena.

To obviate structured solutions, the research program places an emphasis on integrating vision, touch, and proximity sensing in process control. Sensor integration is apparently a prime target in the generally held concensus about gaining flexibility. For instance, the NBS/NASA report (Gevarter, 1982) notes such aims in its synthesis of needed research that drew on surveys and recommendations of conferences and workshops during the previous three years. The implied emphasis is on the integration as well as the generation of sensory data that is, on linking the computation of an understanding of the environment to the mechanical function.

In summary, the DARPA program in intelligent task automation seeks technology development representing a substantial leap forward from current capabilities with a focus on realizing automation in unstructured environment. The necessary intelligence to deal with both uncertainty of the environment and sophistication of the intended task is specifically sought; and, the technological opportunities are expected in linking computation to mechanical function. The choice of scope in carrying out this objective is depicted in Figure 1 below and described in the following sections of this paper.

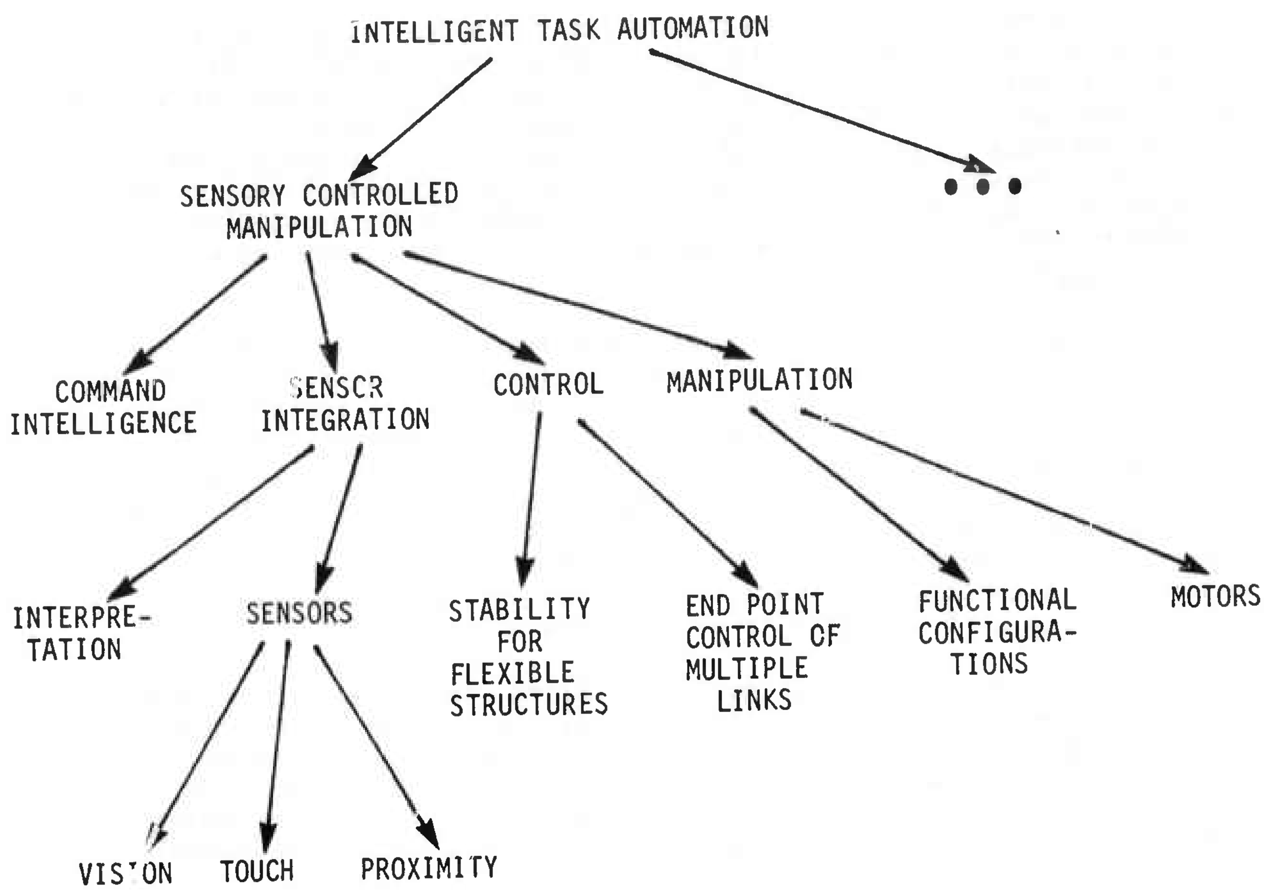

Figure 1. Couplings in DARPA Program

END MANIPULATOR CONTROL

Available technologies present a broad gamut of limitations to achieving the "smart hands" called for in intelligent task automation. The needed dexterity entails rapid movement within the context of the work space, sensitive force control and fine movement enabling the "give" needed for inserting or mating parts, and a secure grasp that accomodates irregular objects. In contract to these needs, manipulators now primarily respond to position control, requiring that the robot's environment be engineered to the same high accuracy as the robot. Large and heavy structures are used to provide stiffness so that end point locations can be accurately inferred from joint angles. Thus, movements are slow and clumsy; and position accuracy is only as good as the accumulation of errors and the stiffness of the members. Designs for multifinger hands, suitable for grasping, have only progressed to the ability to impart some limited motion by a heuristic combination of position and force-controlled fingers.

End point control of the manipulator and the individual fingers is the key to quick and precise actuation with lightweight structures. It is not yet available because robust (stable) control of the flexible structures has not been possible. When torque at one end of a series of links is based on feedback at the other end, any flexibility in the series makes the system inherently unstable. The techniques for stable control using end-point sensing are difficult to perfect. DARPA is now sponsoring research to directly address the integration of end point sensing with efficient stable control.

Specific attention is being turned to developing minimum time algorithms for slewing a flexible robotic arm through a large angle and then touching an object softly. That is, large impulsive "crashes" are to be avoided at the contact. To handle uncertainty in the target object's location, the research will incorporate end-point sensors such as optics, simple range finders, strain-gauge-equipped fingers and proximity sensors. New design concepts for arms are expected that will enable controlling higher terminal speeds without large impact forces even when there is uncertainty in the target's location. For example, mass distributions and flexibility will be varied in design trade-off studies.

Since a number of control modes must be involved, beginning with a large positional slew and ending with force control, methods are under investigation for smooth switching between control regimes while the mechanism is in motion. Initial objectives are to obtain the minimum-time algorithm for the "slew and touch" task. Further investigation of new arm designs will then take advantage of flexibility and distribution of arm control to best accomplish specific tasks.

As control techniques are developed that are tolerant of flexibility in a manipulator's mechanical structure, manipulators can be lightened and made faster. They will be safer to use, less prone to damage from collisions, require less power to run, and cost less to fabricate.

Control of force sensing fingers is also being explored under the current DARPA sponsorship. The control theory for coordinated motion of complex hands developed by Salisbury and Craig (1982) at Stanford University is being pursued. The theory specifies position and force control for the coordinated motions desired in such tasks as insertion where the goal is to minimize transverse forces while exerting a force in the intended direction of the insertion. Such tasks require force control throughout the relative motion and necessitate sensing force and contact for feedback. Several architectures for position and force control of the multiloop mechanisms are being investigated. Preliminary results are appearing for the joint's torque subsystem. The physical dimensions of multi-fingered hands can be optimized on the basis of kinematic performance and the volume of grasp.

END SENSING

Force and contact sensing are also being explored for perceptual information. Components for force sensing are now being perfected that provide force measurements without friction and with little mass between sensor and load. At the command or strategy level in automation for a task, contact sensing provides the information for inference and estimation of geometric and dynamic properties of loads and the environment. Contact of individual fingers provides an estimate of local surface curvature and orientation, while several point contacts on several fingers provide gross orientation and curvature, e.g. fingers wrapped around a cylinder. Integrated data from fingers moving over a surface should reveal surface shape and dynamic properties of objects. As this research progresses, it is expected that strategies in hand control will evolve from experiements. Manipulation rules for re-orientation of grasped objects within the hand is one of the goals.

Integrating vision, range sensing and proximity sensing with the force and contact sensing is also being addressed. There are two levels of intended integration in the hierarchy of command and control -- at the command level for intelligent planning of the task actions, and at the control level for tracking.

Vision and image analysis are major research areas of the same magnitude as the intended focus on ITA (see, for instance, the survey by T. Binford, 1982). Results from vision research at leading institutions will be extensively drawn into the investigations of the command and control processes for ITA. Understanding how vision integrates with other sensors is the major objective, rather than the vision science per se. In particular, the research foundations for the use of models in sensory processing and interpretation are being explored in relation to representations of sensor estimates as geometric constraints.

RANGING AND 3-D SENSING

The practical benefits of ranging systems are beginning to be recognized. The data so gathered may be organized in depth maps, range images or like forms of 3-D "vision." Three-dimensional sensing has the same aim as other forms of computer vision -- the higher level representation of the scene for purposes of comparison or recognition.

When a manipulator is on the move in dealing with a dynamic situation, it is necessary that it work with shape in its three dimensional space. The system should be capable of dealing with information acquired piecemeal from different vantage points. In fact, arrangements as have been tried by G. Agin (1979), among others, have shown the advantages of moving the sensors for the express purpose of obtaining more detailed information about the environment, such as seeing around occluding objects.

In research receiving support by DSO and IPTO jointly, a goal is set on classifying objects and determining their position and orientation with a ranging system. The activity is constructing a sensing system for generating light-stripe range data from multiple points of view and exploring concepts for gaining speed and accuracy in its operation. The data analysis developments are devising advantageous data structures for indexing the data and controlling image scanning. Generalized cylinders make up the low-level primitives in range data.

Identification of objects is sought on the basis of a preponderance of evidence from a matching process.

PROXIMITY SENSING IN ASSEMBLY

Of special interest is the role of proximity sensing in relation to the vision perspective at relatively long ranges and the perspective of touch sensors at contact. Short-range proximity and part-presence sensors can possibly overcome finger shadowing of a vision sensor and may enhance the ability to cope with unstructured or cluttered fields of view as occur with some assembly tasks. Operations involving the important assembly tasks of mating shafts into holes and bearings onto shafts without jamming can benefit from improvements in accuracy and speed. Current capabilities for such automation of assembly particularly lack ability to detect whether the assembly has proceeded properly.

A current objective of DARPA supported research is to demonstrate the capabilities of an acoustic sensing method based on phase monitoring as a means of detecting and controlling the performance of robotic assembly. Demonstration of shaft and bearing mating is intended. The research extends the technology of an automated positioning system based on phase monitoring of an array of acoustic sensors (microphones) as developed earlier by J. Tavormina (1978) and S. Buckley at MIT. A manipulator was positioned by phase measurements from the acoustic sensor array, locking onto an objects position. All the necessary elements of a robot for assembly were demonstrated and later work at MIT showed that the sensor system could provide sufficient accuracy for commercial robots.

Now software is under development for detailed processing of the sensor data and for integrated control of a commercial robot. The software development is including the development of various algorithms to interpret phase information and couple control to the robot. The investigations are addressing "matrix" algorithms for interpreting phase information, and "proximity" algorithms to detect range and direction data in less structured environments. The goal of the proposed work is to demonstrate assembly of mating parts with response sufficiently rapid for industrial application (typically one second for shaft or bearing assembly).

MICRO-MINIATURE MOTORS

Mechanical concepts for the dexterous hand have made extensive progress. The jointly conceived "Stanford-JPL hand" has appeared prominently in the popular press, presumably by virtue of appearing to borrow heavily from nature by using tendon-like cables to actuate its fingers. Motors are mounted on the forearm to avoid encumbering the fingers. The tendon-like design allows three joints, on each of three fingers, with an overall geometry similar to that of a human hand. The nine degrees of freedom provide a firm basis for dexterity.

The "tendons" are cables and the electromechanical devices are conventional motors, nonetheless. Electric motors have a number of inherent problems which limit their effectiveness in application to fine-motion manipulators. Such limitations are addressed by another research effort currently supported by DARPA aimed at capitalizing on the lessons from biology about the structure and scale of natural muscle.

While electric motors are well suited for applications such as fans, disc drives, pumps, etc., their relatively low output torques require use of transmission systems for the high-torque and low-speed operation in a servosystem or robotic application. Transmission systems introduce a number of serious limitations on electric motors by compromizing the dynamic performance. Dynamic characteristics of the motor such as armature inertia and damping are affected by the square of the transmission ratio. Transmissions also impact efficiency. For example, high performance planetary transmission, utilized extensively in today's aircraft industry, drop efficiencies into the range of only 50%.

A more desirable option for an electric actuator in a manipulator of the size of the human hand would be a motor which itself produces high torque at lower speed and eliminates the need for transmission systems altogether. However, even without transmissions, the high mass density of most magnetic materials and electric conductors, makes the power-to-weight ratio of electric motor systems extremely poor. When compared to hydraulic, pneumatic, and combustion based systems, electric motors are inferior by a full two orders of magnitude.

The lessons from biology are that natural muscles are fast, efficient, develop large forces (60 pounds per square inch), can be configured in a variety of sizes, and operate with an extremely low output impedance. Muscle has: (1) a large number of small force-generating elements mechanically connected in parallel; and (2) close proximity between force-generating elements (charges), taking advantage of inverse square laws to produce high local field strengths which increase the force generated per charge. Muscle thereby avoids the use of gross fields and employs instead a fine tapestry of field interactions locally commutated for the production of smooth output forces.

It is expected that the feasibility of field actuation systems with microgeometric structure can take advantage of the understanding of muscle. Already, the understanding of sensor based manipulation benefits from developments in institutions engaged in biomedical design. Artificial hand and hook designs are providing insight about grasping functions and structural configurations. Also, sensory feedback systems developed for prosthesis, including touch sensing and slip detection in multi-axis control, provide methodologies for complex geometry manipulators.

The goal of investigation into field actuation systems of the nature of a volumetric array of charges is to produce contractile or repulsive forces in high density systems matching biological muscle in efficiency, speed, specific force, packaging flexibility and low output impedance. Manufacturing is also being addressed, including the possibilities of adopting the precision techniques of the microcircuit industry. This research is anticipated to offer the possibility of order-of-magnitude improvements over today's electric, hydraulic and pneumatic devices in efficiency, power-to-weight ratio, and combined high-torque/low-speed characteristics.

THE INTEGRATION TECHNOLOGY

In addition to supporting the technology developments described above, DARPA has also linked with AFWAL in a substantial single program to push the state-of-the-arts and force the technology breakthroughs so that a significant demonstration is conducted in intelligent task automation. The objective includes building individual components of the ITA subsystem, integrating the subsystem, and demonstrating applicability to defense manufacturing and flexibility for application to other military applications.

The Air Force context for the program is described by W. Kessler (1982) in terms of the Air Force's new initiatives in manufacturing sciences. The existing materials research and development, manufacturing technology programs, and ICAM activities are augmented by the initiatives. And, the emerging science related to manufacturing is substantially enhanced in order to provide the manufacturing technology base for the defense-related factory of the future. The ITA activity is envisioned as providing the cornerstone for payoffs in intelligent tasks of factories-of-the-future and military operations.

It is intended that the individual ITA technology R&D and the joint DARPA-AF ITA program be complementary. The ITA subsystem demonstration (being specifically defined in the first phase of the investigations) is intended to provide the focal point for developing the requisite integration of technologies. Pragmatic emphasis is placed on the technology to <u>integrate</u> advanced concepts, thereby complementing the attention to <u>concept formulation</u> in the individual areas of related technology. Advancing the technical means (gripping, sensing, viewing, recognizing and understanding the environment, controlling manipulation, and intelligently providing command of the task) within the same time frame as concept formulations means that the job of integration remains highly unknown with persistently uncertain requirements. All-in-all, the technological opportunity to integrate advanced technologies provides considerable leverage for the individual technical means.

SUMMARY

Specific opportunities for substantial technical advance and breakthrough are presented in a somewhat narrow field of automation pertaining to the higher order linkage of computation to mechanical function. The payoffs of pursuit of these opportunities are expected to amplify the ultimate operational applications of intelligent task automation at large.

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